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Numerical investigation of spray characteristics of an air-blast atomizer with dynamic mesh

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ABSTRACT

In this paper, a numerical simulation of an air-blast atomizer using OpenFOAM software is performed to evaluate the effects of geometrical parameters and flow conditions on spray characteristics. The method used in this numerical simulation is discrete droplets tracking-based Eulerian–Lagrangian approach. In the primary breakup of liquid jet modeling, the Rosin–Rammler distribution function and in modeling the secondary breakup phase, the Kelvin–Helmholtz, Rayleigh–Taylor (KHRT), and the TAB models are used and compared. The simulation results show that the KHRT model has reasonable prediction of atomization characteristics and, at a specific Weber number, SMD increases with raising liquid port diameter. However, in high Weber number, this parameter has little effect on SMD. In addition, gas–liquid injection angle has an insignificant effect on the penetration depth of spray, while increasing the liquid port diameter decreases it considerably.

1. Introduction

Atomization is a process in which fluid bulk converts to very small droplets by passing through a nozzle. The set of droplets dispersed into a gaseous atmosphere is called spray. An atomizer is a device used to generate spray from the liquid bulk. Atomization is widely applied in different fields such as agriculture, pharmacy and especially in the analysis of fuel injection to combustion chamber of gas turbines and internal combustion engines. The combustion efficiency and associated emissions are affected remarkably by atomization quality, evaporation of the fuel droplets and mixing of air and fuel. The characteristics of spray and its dynamics are very important in the investigation of flame instability, safety and efficiency of combustion and the mechanisms of formation and destruction of pollutants. Today, in order to improve the efficiency of combustion and reduce the generation of pollutants, it is required to understand and control spray and its combustion [1].

In the most of atomizers, the main cause of spray generation is a high relative velocity between gas and fluid phases. Atomizers are classified into different types based on the mechanism of creating the relative velocity. The most important types of atomizers are pressure and twin-fluid atomizers. Pressure atomizers discharge the liquid with a high relative velocity to gaseous atmosphere. An alternative approach is to inject a slow moving liquid into a high-velocity gas stream. Atomizers that use the latter mechanism are known as twin-fluid or air-blast atomizers which have many advantages over pressure atomizers. These atomizers require lower fuel pressure and generate sprays of higher quality. In addition, because of appropriate mixing of air and fuel prior to combustion process, less pollutant is produced. There are two types of twin-fluid atomizers called air-blast and air-assist. In both atomizers, the kinetic energy of air stream is used to convert the fuel jet or sheet into ligaments and then drops. The main difference between these two atomizers is airflow rate. In the air assist atomizers, airflow rate is very low compared to air blast atomizers. However, since there is no constraint on air pressure in the air-assist atomizers, it is possible to compensate low airflow rate by an increase in air velocity. Thus, air-assist atomizers use low airflow rate with high velocity, whereas because of limitated air velocity in the air-blast atomizer, a larger quantity of airflow compared to air-assist atomizers is needed to achieve desired atomization [2].

Spray cone angle, Sauter mean diameter (SMD) and penetration depth are important parameters of spray that have direct effects on atomization efficiency [3]. The spray cone angle is the angle between central axis and tangent line to the outer edges of spray. Because of the nonhomogeneous nature of breakup and atomization process, a spray is a nonhomogeneous mixture of droplets with different sizes, so it is necessary to determine Sauter mean diameter parameter and droplets distribution. Another functional characteristic that must be considered is the penetration depth which is the distance between orifice and the spray tip.

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Nomenclature

P	Pressure	T	temperature
u	Velocity	e	Internal energy
u_{rel}	Relative velocity	δ	Kronecker delta
$\mathbf{u}$	Velocity vector	τ_{ij}	Shear stress
$\mathbf{x}$	Location vector	τ_d	momentum relaxation time
m	mass	τ	characteristic time
r	droplet radius	We	Weber number
SMD	Sauter Mean Diameter	Re	Reynolds number
d	Mean particle size of the distribution	α	Liquid injection angle
$\mathbf{F}$	Force vector	l	Length of gas–liquid mixing chamber
C_D	Drag coefficient	d_l	Liquid port diameter
t	Time	d_g	Atomizer exit diameter

Liu et al. investigated a coaxial air-blast atomizer experimentally. They observed that increasing the liquid nozzle diameter raises SMD of droplets and these changes are affected noticeably by liquid ratio to gas mass flow rate. They also showed that if the ratio is kept constant through increasing Weber number, the SMD initially declines and then grows [4].

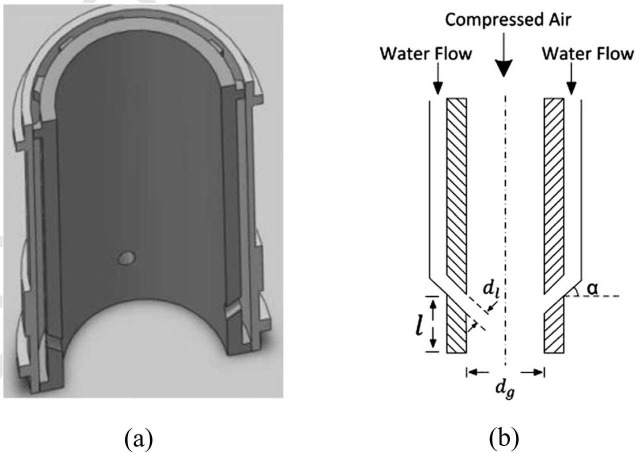
Sinha et al. experimentally studied the characteristics of an air-blast spray of cross-flow type for various flow conditions. They observed that the spray penetration primarily depends on the momentum ratio and that high GLR (gas to liquid ratio) results in better dispersion of spray. Their study showed that SMD increases with distance from the injector wall. Moreover, SMD values decrease along the gas flow direction [5].

Ma et al. empirically investigated the characteristics of two air-blast atomizers with different form in the gas–liquid mixing. They examined the effects of air pressure, liquid pressure and gas and liquid droplets mixing method on spray angle and velocity field. Their results showed that spray angle is highly dependent on gas flow pressure. At high gas pressure, the spray angle depends on gas and liquid mixing method. They also found that spray angle and spray velocity are not sensitive to liquid pressure change [6].

In another study by Costa et al. [7], an experimental investigation was performed to study the spray characteristics of the injection of angled liquid (water) into subsonic cross-flows. They studied the characteristics of spray for high liquid to air momentum flux ratio (at the order of 25 to 637) and low aerodynamic Weber number (at the order of 0.1 to 3.42). They found that nozzle injection angle has a significant effect on the jet penetration and atomization quality. However, liquid-to-air momentum flux ratio has a lower effect. They observed that the breakup length decreases with higher nozzle injection angle and increases with higher liquid-to-air momentum flux ratio. Their results also show that droplets' mean diameter diminishes with increasing the nozzle injection angle and it is affected only significantly by the liquid-to-air momentum flux ratio, either through changes in air velocity of the cross-flow or through the liquid flow rate.

Although many empirical studies have been conducted on atomizers, but the numerical studies on this context are few. Huang and Lipatnikov from Chalmers University have done a numerical simulation of hollow-cone sprays by OpenFOAM software that has a high capability in spray modeling. They applied some modification on KHRT model and their results indicate that a combination of the Rosin–Rammler distribution with Reitz–Diwakar secondary breakup model and modified KHRT model lead to the optimum compliance with the measured liquid penetration length and SMD under the conditions of their study [8].

Due to time-consuming and expensive experimental investigations, today numerical simulation of atomizers are of more interest. It is necessary to compare experimental and simulation results to reach a reliable numerical solver. In the modeling of atomizers, there are no comprehensive solver because of complexity of sprays and variety of injection pressures. Combination of numerical and experimental investigations is an appropriate approach to define constants of equations in the solver model for a unique atomizer. In this paper, OpenFOAM software was used to simulate an air-blast atomizer and the results of numerical modeling were compared with experimental data from the previous paper. The experimental study is performed using Malvern Master Sizer *x* that measures droplet diameters at 5 cm from the outlet of atomizer. Moreover, in that study a high-speed digital camera (Mega-Speed MS50K) was employed to determine spray angle and penetration depth [9,10].



(a) (b)

Fig. 1. Two-fluid atomizer used in the study: (a) 3-D view; (b) a schematic view [9].

2. Numerical model

A schematic and a photographic view of atomizer are shown in Fig. 1. The compressed and high-velocity air passes through the central duct of atomizer and the liquid is injected from annular passages that end in six inclined holes. The holes are equally arranged on the circumference of the atomizer at a sector angle of 60°. The geometrical parameters of atomizer such as injection angle of the liquid, atomizer outlet diameter, liquid outlet diameter and liquid–air mixing length are shown in Fig. 2(b) [9].

For simulating the spray flow, OpenFOAM software has been used which is an open-source fluid software that has high capability to simulate a wide range of two-phase flows. In this study, the sprayDyMFoam solver has been used which is capable of solving compressible laminar and turbulent two-phase flows. This solver uses PIMPLE algorithm for coupling pressure and ve-

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